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13. ABSTRACT (Maximum 200 words)

Research instruments, consisting of 2 workstations, 14 sonic anemometers, and 28 fine wire thermocouples, were acquired with funds provided under this grant. This equipment was primarily intended for innovative studies of the resolvable and sub-grid turbulence and fluxes pertinent to large eddy simulation models of the atmospheric boundary layer. This report describes the equipment purchased and gives a brief description of equipment use in seven different field studies of atmospheric boundary layer fluxes.

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1. Equipment acquired

With the grant funds we acquired 2 Sun Ultra workstation systems, 14 Campbell CSAT3 sonic anemometers, and 28 fine-wire thermocouple probes and cables.

The Sun workstations are used for data acquisition with our ASTER system, and for postprocessing of the resulting data. They replaced the original ASTER system computers that were purchased ca 1992 and were outdated. Sytem 1 totaled $5847 (workstation $3550, internal hard drive $360, memory expansion $340, Sun monitor $1000, PCI adapter $597). System 2 totaled $5972 (workstation $3550, Sun PCI co-processor $1125, internal hard drive $360, memory $340, PCI adapter $597).

The 14 CSAT3 sonic anemometers totaled $104,740. The thermocouples and probes totaled $4202.80.

2. Research projects on which equipment has been or will be used

a. Area-averaged surface fluxes

Our original proposal included description of a new technique for inferring area-averaged surface fluxes of a species from an array of measurements of horizontal speeds and species differences. We proposed to test the technique at our Rock Springs field site. We recruited a graduate student in the fall of 1998 to carry out the project but he left Penn State in early summer, 1999 for the job market before he had made significant progress on the array measurements.

b. Resolvable and subgrid-scale array measurements

In summer 2000 we lent 7 of the CSAT3 sonics to the National Center for Atmospheric Research (NCAR) for use in a field experiment on resolvable and subgrid-scale (SGS) turbulence relevant to large-eddy simulation (LES). LES is one of the principal tools used for studying geophysical turbulence, but is far from ideal because of its crude treatment of small-scale turbulence processes. Current SGS models in LES can capture average statistical properties (such as the mean dissipation rate) but are very poor at representing local interactions between resolved and SGS eddies.

We have developed an array technique for measuring SGS stresses (Tong et al., 1998). Early results with the array, which requires 14 sonic anemometers, (Tong et al., 1999) were promising. Subsequently, a group of NCAR scientists (Chin-Hoh Moeng, Tom Horst, Peter Sullivan, Don Lenschow and Steve Oncley), working with us, MMM visitor Jeff Weil, scientists from the Johns Hopkins University (Charles Meneveau, Marc Parlange, Jan Kleissl), and UCLA (Bjorn Stevens and Jianjun Duan), proposed, designed and participated in a field experiment (SGS-2000), which took place during September 2000 near Kettleman City, California. We provided 7 of the 14 sonic anemometers that were arranged in space to measure turbulent motions in 2D horizontal planes. The turbulent fields will be decomposed into resolved and SGS fields, mimick-

ing conditions in LES near a solid surface. Important SGS model properties such as SGS stresses and resolvable strain rate can be obtained from the field data. This data set is now being calibrate and then will be analyzed to extend the earlier results to a wider range of stabilities.

c. Vertical Transport and Mixing Experiment (VTMX)

We lent two CSAT3 sonic anemometers to a University of Massachusetts group under Steve Frasier for use during the Vertical Transport and Mixing Experiment (VTMX) held in October 2000 in the Salt Lake Valley. These were used to provide surface winds and fluxes to complement radar and sodar measurements obtained at their field site. In VTMX, the UMass group's primary objective is to use volume-imaging UHF radar and S-band FMCW radar to determine the minimum spatial and temporal scales at which useful and reliable remote measurements of turbulence are obtainable with current boundary layer profiler technology. They are working with us to apply the measurements of these sensors to validation of turbulence closures under stable conditions.

d. Turbulent fluxes via the footprint technique

Penn State Geosciences graduate student Cindy Werner used one of our CSAT3 sonic anemometers in August, 1999 to make the first measurements of the turbulent flux of CO_2 in a hydrothermal region. Working near Mud Volcano in Yellowstone National Park, she used the sonic and a Li-Cor CO_2-H_2O analyzer at a height of 3 m to measure the vertical turbulent flux of CO_2 downwind of spatially nonuniform surface emissions of CO_2. She found that the measured turbulent flux $\overline{wc}$ at height z_m agreed well with values calculated with the "footprint technique" (Horst and Weil, 1992), which relates $\overline{wc}(z_m)$ to an integral of the footprint function f over the upwind distribution E of surface emissions:

$$\overline{wc}(z_m) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} E(x', y') f(x - x', y - y', z_m) dx' dy'. \tag{1}$$

She measured $E(x, y)$ directly with the chamber technique. She found that the differences between direct measurements of $\overline{wc}$ (20- to 60-minute averages) with the sonic and Li-Cor and values computed through the footprint technique and Equation (1) varied between 30% and a factor of 2, which is within the error associated with extrapolation of chamber measurements of surface fluxes in this hydrothermal region.

e. Scalar flow-distortion studies

The successful measurements of CO_2 fluxes downwind of nonuniform surface emissions described in subsection *d* were possible for two reasons. First, the in-depth knowledge on micrometeorology that has been gained over the past few decades allowed Horst and Weil (1992) to calculate the footprint function f fairly reliably. Second, the advances in sonic anemometry engineering and design embodied in the Campbell CSAT3

now make possible extremely reliable, accurate measurements of turbulence. After the field experiment described in subsection *b*, NCAR's Tom Horst reported to the participants "We had zero problems with the CSAT sonics in roughly $16 \times 24 \times 30 = 11{,}520$ sonic-hours of operation and never used our reserve sonic."

The CSAT3 sonic is the only one known to us that meets the design criterion of Wyngaard (1987) that the sonic array be symmetric about its horizontal midplane. This ensures that flow-distortion effects on scalar fluxes are minimized. In summer 2000 Meteorology graduate student Darin Ometz and Wyngaard studied flow distortion effects on scalar fluxes at our Rock Springs field site, extending our earlier work there on velocity statistics (Miller et al., 1999). As in that experiment, we distorted the velocity field in one CSAT3 by mounting a 30-cm diameter two-dimensional circular cylinder slightly downwind of it. We then measured vertical temperature flux with that CSAT3 and with another mounted at that height in the distortion-free air two meters to the side. The object was to simulate, in exaggerated form, the effect on scalar flux measurements of flow distortion caused by mounting brackets, booms, towers, etc. and to test the simple theory of Wyngaard (1981) for those effects.

The flow distortion errors in temperature flux ranged from −50% to +80% and agreed well with those predicted by the theory. We are preparing a journal article on these results.

f. Atmospheric acoustics studies

We lent two CSAT3 sonics to Dave Swanson of Penn State's Applied Research Laborarory, who studied the dependence of acoustic coherence on turbulence conditions and the direction of propagation relative to the mean wind at the Rock Springs site. The experiment had three sound sources (nominally upwind, downwind, and crosswind), and a three-axis orthogonal microphone array. In this experiment, funded by The Army Research Laboratory (monitor Keith Wilson) the entire acoustic coherence "tensor" was simultaneously measured for the first time. The data have not been analyzed yet.

g. Trace-constituent fluxes

We provided two of the three sonic anemometers that are being mounted on a 500-m television broadcast tower near Waco, Texas. These sonics will be paired with Li-Cor infrared gas analyzers to measure a vertical profile of the turbulent transport of CO_2, H_2O, virtual temperature, and momentum above the surrounding scrub woodland and agricultural fields. The sonics will provide direct observations of turbulent profiles deep into the ABL. Paired with high-precision CO_2 mixing ratio measurements, these data will also provide direct observations of local ecosystem-atmosphere exchange of CO_2 and H_2O as well as the relationship between the local surface exchange, boundary layer budgets of these scalars, and larger scale transport across the southern Great Plains. Paired with a second tall tower site in northern Wisconsin, and an intermediate height tower at the ARM-CART site in Oklahoma, this tower will provide a southern boundary point to observe the land surface modification of airmasses that move northwards from the

Gulf of Mexico across the Great Plains. This study is being conducted by Peter Bakwin (NOAA-CMDL) and Kenneth Davis (Penn State).

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